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# **INTER-LABORATORY COMBAT HELMET BLUNT IMPACT TEST METHOD COMPARISON**

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**Approved for public release; distribution is unlimited**

**U.S. Army Natick Soldier Research, Development and Engineering Center  
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STIFFNESS	TEAM WENDY	HEAD(ANATOMY)	WOUNDS AND INJURIES			
VELOCITY	TEST METHODS	IMPACT VELOCITY	PROTECTIVE EQUIPMENT			
EQUIPMENT	TEST FACILITIES	SIZES(DIMENSIONS)	TEST AND EVALUATION			
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## Preface

Blunt impact testing of helmets was performed and statistical analysis was completed in order to verify inter-laboratory consistency. Two laboratories were previously validated for blunt impact testing of Army combat helmets: the U.S. Aberdeen Test Center (ATC) and National Technical Systems (NTS) Chesapeake Testing Services (CTS). A third organization, Natick Solder Research, Development and Engineering Center (NSRDEC) was evaluated and compared to ensure that testing conducted there would be consistent with the other two laboratories.

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# **INTER-LABORATORY COMBAT HELMET BLUNT IMPACT TEST METHOD COMPARISON**

## **Introduction**

As the medical community learns more about brain injury, the importance of blunt impact mitigation becomes ever more apparent. As such, it is critical to make sure that research labs are not only capable of performing testing in this field but also show inter-laboratory consistency and reproducibility. This study is a comparison between the two validated blunt impact testing labs (Aberdeen Test Center (ATC) and National Technical Systems (NTS) Chesapeake Testing Services (CTS)), and Natick Soldier Research Development and Engineering Center (NSRDEC).

NSRDEC has acquired new blunt impact test equipment including the Cadex uniaxial monorail drop tower. This equipment has become the unofficial standard for military blunt impact testing. This is a significant upgrade in precision and performance over the U.S. Testing Co. Inc drop tower NSRDEC had been using. The primary objectives of this study were to validate and verify that NSRDEC's new equipment and personnel are conforming to the current standard operating procedure and to ensure that inter-laboratory data are similar.

## Methodology

### Laboratories

Three primary laboratories were evaluated: NSRDEC, ATC and CTS, a Division of NTS. Both ATC and CTS have been identified as laboratories compliant with the official test method for US Army helmet blunt impact testing.

ATC is the Army's official test center for all protective equipment compliance testing. ATC developed the official test procedure (ATC-MMTB-IOP 029 - Blunt Impact Testing) [1], whereas CTS has been verified by ATC as the only other test laboratory in compliance with their test procedure.

### Test Samples

The Advanced Combat Helmet (ACH) is in short supply, making them difficult to procure. Product Manager Soldier Protective Equipment (PM SPE) was able to supply enough ACH helmets for this effort with the caveat that not all of the helmets were from the same production lot or same manufacturer and that some were supplied with installed Helmet Sensors while others were not. All helmets were provided with full suspension systems, including the Team Wendy Zap pads and the ACH Retention System.

Each laboratory was provided with 8 ACHs of each size (Small, Medium, Large and X-Large) for a total of 32 helmets. This provided each test laboratory the six required helmets of each size for the test and two contingency helmets of each size. A list of those helmets can be found in Appendix A – Advanced Combat Helmets, Furnished.

### Test Method

The purchase description CO/PD-05-04 [2] for the ACH specifies the use of DOT FMVS218 with some exceptions. This test method leaves a lot of room for interpretation and the variation in test results can be seen in historical data [3]. The recently developed Internal Operating Procedure (IOP) from ATC incorporates all requirements from the ACH purchase description, while removing a significant amount of user interpretation from the test method. This effectively improves the reproducibility of the procedure. All tests and collected data for this effort complied with ATC's IOP.

Head-form acceleration and drop velocity data were collected for each impact. Velocity immediately preceding impact is collected as a single data point through a laser time gate while acceleration is collected continuously throughout the event. The Cadex data acquisition system collects data at a frequency of 33 kHz and filters the data through the CFC 1000 filter. The CFC 1000 is a 4-pole 1650 Hz low-pass Butterworth filter specified for head impact acceleration data by Instrumentation for Impact Test, SAE standard J211-1 [4]. Although the entire curve is collected, the interest of this project team solely lies in the peak or maximum acceleration the head-form experiences during impact.

### Approach

The Test Laboratories followed the official test procedure (ATC-MMTB-IOP 029 - Blunt Impact Testing). A brief overview is described in the following subsections.

### Preparation

Six helmets of each size are prepared prior to testing. The helmets must be weighed, labeled and the Team Wendy pads must be placed into their corresponding locations as specified in the procedure. Two of each size helmet must be placed into a cold ( $-10 \pm 3$  °C) environmental chamber and two of each size helmet must be placed into a hot ( $54.4 \pm 3$  °C) environmental chamber for at least 12 h. The last two helmets must be conditioned at ambient ( $21 \pm 10$  °C) for at least 12 h.

On test day, just prior to the test, the Cadex drop tower is verified by using a calibration check procedure. The Cadex software is programmed for the test plan with correctly identified test sample nomenclature.

### Test

The helmets are tested in groups by size. Each helmet is impacted in seven different locations, twice. The helmets impact a hemispherical anvil, apex to apex. The seven locations are impacted in order as follows: Crown, Front, Rear, Left Side, Right Side, Left Nape and Right Nape. The second impact occurs between 60 and 120 s after the first. The helmet is fitted onto its corresponding Department of Transportation (DOT) head-form incorporating a foam chin. The front straps are tightened halfway and the back straps are tightened until the helmet is snug. The helmet is positioned to what is known as Helmet Position Index (HPI), a measured distance between the brim of the helmet and the first line on the DOT head-form. The hot and cold conditioned helmets shall not be left outside their respective environmental chambers for more than 5 min. Any helmet which is left out for more than 5 min must undergo the full conditioning process again prior to continuing the test. All impacts are conducted at a velocity of 10 ft/s (3.048 m/s) with a tolerance of  $\pm 0.3$  ft/s ( $\pm 0.091$  m/s). A laser gate velocity detector is used to record the velocity at every impact and a uniaxial accelerometer (vertically located at the head-form's center of gravity) is used to record acceleration during impact. Only the peak acceleration is evaluated.

Each Test Laboratory had unique interpretations of the test method. Some of those quirks are identified in Appendix B – Test Lab Information.

### Post Test

Once the test is completed a second calibration check procedure is performed to ensure the accelerometer has not drifted during the test.

## Results

Nearly all test variables (size, condition, impact location, and impact number) result in observably different responses. Some parameters show a much greater difference in peak acceleration response than others. For example, the front impact location exhibits a dramatically greater response peak acceleration than the other locations and the cold condition on average resulted in the highest peak accelerations due to the increased stiffness of the pads. Contrastingly, there was little difference between the hot and ambient conditions and between the crown and rear impact locations.

Some impact locations are more difficult to test. The nape locations, due to the head-form position, are known to be difficult to impact consistently due to the helmets' tendency to fall backward (towards the back of the head-form). This problem is seen when using the H-back-style ACH Retention System, standard with the ACH. The HPI only aligns the front of the helmet with the head-form. Depending on the pad thickness and stiffness (which changes after impacts and environmental conditioning) the helmet may be aligned in the front but not in other regions due to a difference in stand-off.

Figure 1 (Left) depicts an example of a typical acceleration response. A first and second impact can be seen on the rear location of a hot conditioned ACH. Most impact locations result in a single, mostly parabolic, response as shown. Variations from impact to impact are seen due to geometry and pad interaction dependent on the impact location. Figure 1 (Right) depicts a complete data set of peak accelerations for a single "hot conditioned" ACH in the test method. The column on the left denotes the first impact at each impact location and the column on the right of each impact location denotes the second impact, tested 60 to 120 s later. The second impact generally results in a higher peak acceleration. The trend was exhibited for all conditions. This is due to the pad compression caused by the first impact. Eventually the Team Wendy pads recover, but the time between impacts does not permit a full recovery.

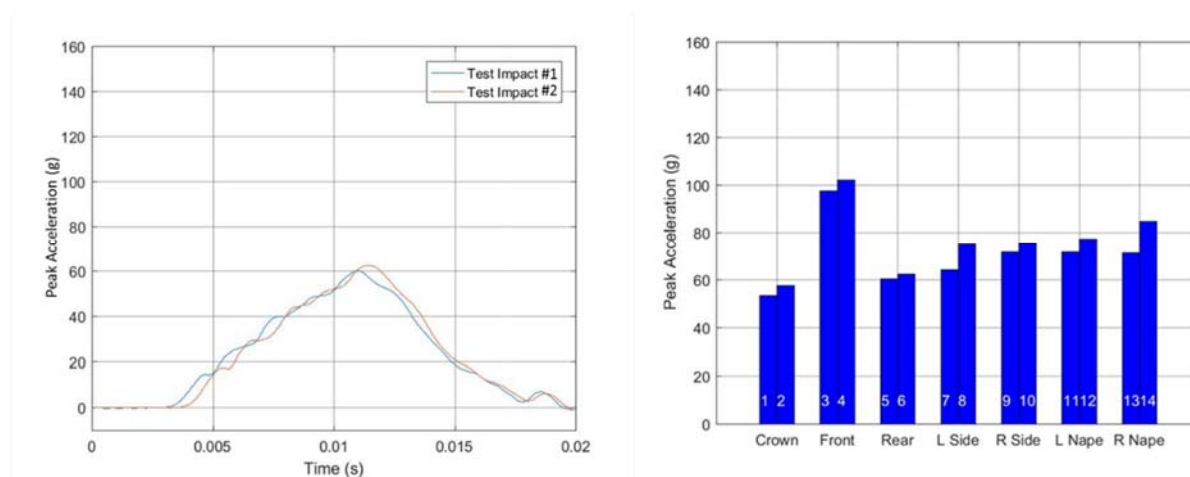


Figure 1. (Left) Typical impact data; (Right) Peak acceleration data set, NSRDEC - hot condition - size large

In the following sections, the three laboratories are compared. Each section breaks the data out in a different way using the recorded peak acceleration as the primary data point. Statistical and empirical methods are used to analyze the data and results.

## Inter-Laboratory Comparison

This section aggregates all data points comparing the average peak acceleration of all helmets by each of the three Test Laboratories (shown in Table 1). This data set shows a top level comparison between the Test Laboratories. In general it is found that CTS trends towards a lower peak acceleration, ATC trends higher, and NSRDEC is somewhere in between. Peak acceleration was the focus of this report but the entire acceleration curve may be of interest. Acceleration corridors comparing the three Test Laboratories can be found in Appendix B – Acceleration Corridors. At each Test Laboratory, all of the helmets evaluated easily passed the requirement, as expected. The test method does not have any statistical requirements, only that the evaluated systems do not exceed 150g at any impact. The ACH system has been designed to achieve peak accelerations under 150g for all impacts when tested in accordance with ATC-MMTB-IOP 029. Each lab replicates this crucial result. A line is depicted in Figure 2 at the 150g acceleration point; all data points in the test are below this line. All box plot whiskers are positioned at 1.5 times the interquartile range and any dots above or below the whiskers are denoted as outliers. This data set is a composite of many variables. Outlying data points are not true outliers, but they do depict extrema. Despite CTS having the highest standard deviation, it had the lowest number of outliers. NSRDEC had an intermediate standard deviation, but the largest number of outliers. For NSRDEC and CTS, all outliers occur in the front location; ATC has two outliers in the Left Nape location and one in the Front Location.

Table 1. Data aggregate by Test Laboratory

N=336	All Sizes, Conditions, Impacts, and Impact Locations		
Test Laboratory	ATC	CTS	NSRDEC
Peak Acceleration (g)	78.7	73.5	75.5
Standard Deviation	15.4	17.5	17.1

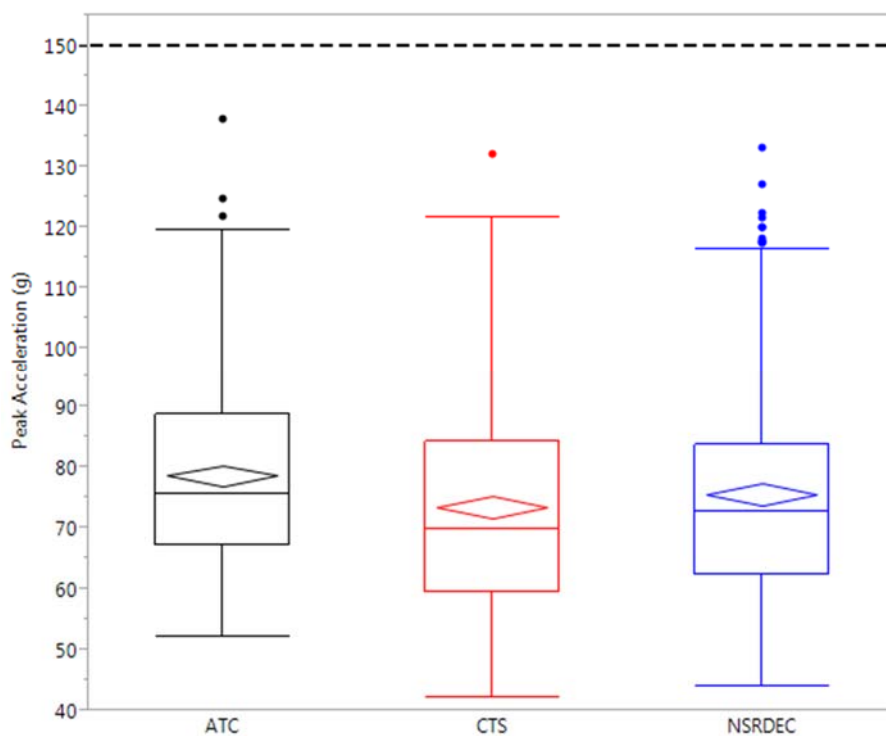


Figure 2. Box and whisker plot (data aggregate) by Test Laboratory

## Recorded Velocity

The target velocity of the test was 10 ft/s (3.048 m/s) with a tolerance of  $\pm 0.3$  ft/s ( $\pm 0.091$  m/s). In all cases, velocity was recorded using a laser gate and flag affixed to the drop carriage as supplied with the Cadex Uniaxial Monorail. Velocity is calculated by recording the time duration that the laser is blocked by the flag, which is a known length. Each Test Laboratory achieved extremely accurate impact velocities, well within the specified tolerance. Additionally, all laboratories show very precise results with essentially negligible variance in velocity. Data depicted in Figure 3 were aggregated from all impacts. Sample sizes for each test lab were  $N=336$ .

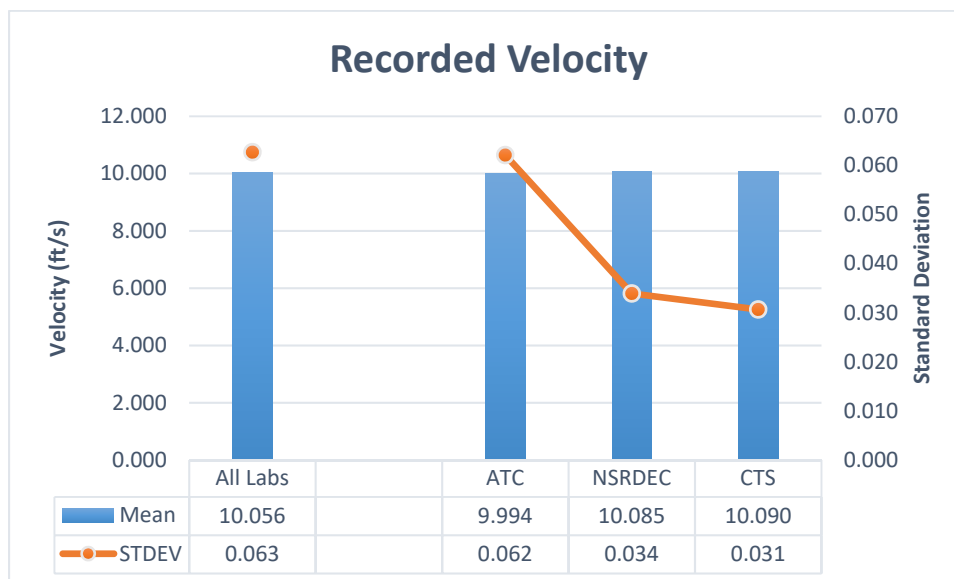


Figure 3. Measured impact velocity

## Comparison by impact location

There are seven different impact locations called out in the test method. Each location is impacted twice per helmet, separated by a time interval between 60 and 120 s. The locations are identified by rotating the head-form to specified angles and locating the anvil such that the lowest tangent point of the helmet strikes the highest tangent point of the anvil at the specified impact velocity.

Here the data are aggregated by impact location and compared between the three test facilities. NSRDEC is found between CTS and ATC at five of the seven impact locations. CTS tends to display the lowest peak acceleration (six locations) when the data are broken out in this manner, while ATC generally exhibits the highest peak acceleration (six locations). The front impact location exhibits the highest standard deviation across all three labs, whereas the side impact location data experienced much tighter standard deviations.

Table 2. Break out by impact location – by Test Laboratory

N=48	Crown			Front			Rear		
Test Laboratory	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC
Peak Acceleration (g)	72.8	67.6	68.3	96.3	95.1	98.3	72.8	71.4	68.1
Standard Deviation	13.4	13.2	15.2	15.2	15.1	17.4	12.3	18.2	12.0

N=48	L. Side			R. Side			L. Nape			R. Nape		
Test Laboratory	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC
Peak Acceleration (g)	71.2	62.5	66.6	70.2	62.0	65.5	83.3	76.3	79.4	84.3	79.8	82.4
Standard Deviation	8.0	7.7	9.1	7.2	8.8	8.5	15.2	15.2	12.1	13.8	15.4	14.4

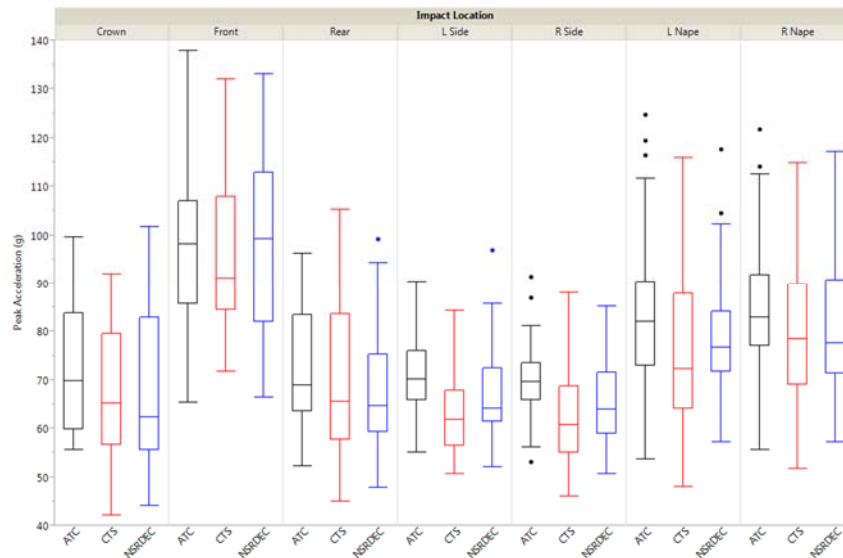


Figure 4. Break out by impact location – by Test Laboratory

### Comparison by size

The ACH comes in four primary sizes. Each size is tested using its corresponding DOT head-form, DOT B for small, DOT C for medium and large, and DOT D for X-large. Six helmets are tested for each size.

Breaking out each helmet size by test laboratory, the same general trends can be seen for each test laboratory, with the larger helmets showing lower peak acceleration than the smaller helmets (Table 3 and Figure 6). This is an interesting result when considering that the larger helmet and hence larger head-form have a greater mass, thus increasing the force that must be attenuated. This is likely due to the suspension system being tuned for an averaged helmet mass and average helmet area, thus making smaller helmets act stiffer during an impact than larger helmets and not fully utilizing the potential of the pad systems. However, as previously mentioned, this test method only utilizes peak acceleration as the primary metric of analysis.

As seen in Table 3 and Figure 6, the smaller size helmets show more variability than the larger sizes. The spike in variability on the size medium may have something to do with the poor fit on the DOT C head-form that was empirically observed. Both the size large and size medium helmet use the same DOT C head-form. While the size large fits fairly well, the size medium requires pressure and pad compression in order to seat on the head-form. This may have the effect of slightly pre-compressing pads (front and sides to achieve required HPI) or influencing the behavior of the helmet following impact. However, the overall trend of decreasing variance with increasing size of helmet and head-form is exhibited throughout all sizes. An investigation of the acceleration data traces (Figure 5) of small and XL helmet impacts shows much smoother curves for the larger size, whereas the curve for the small helmet shows small perturbations throughout the profile. This indicates a better coupling between the helmet and head-form for larger sizes in the methodology.

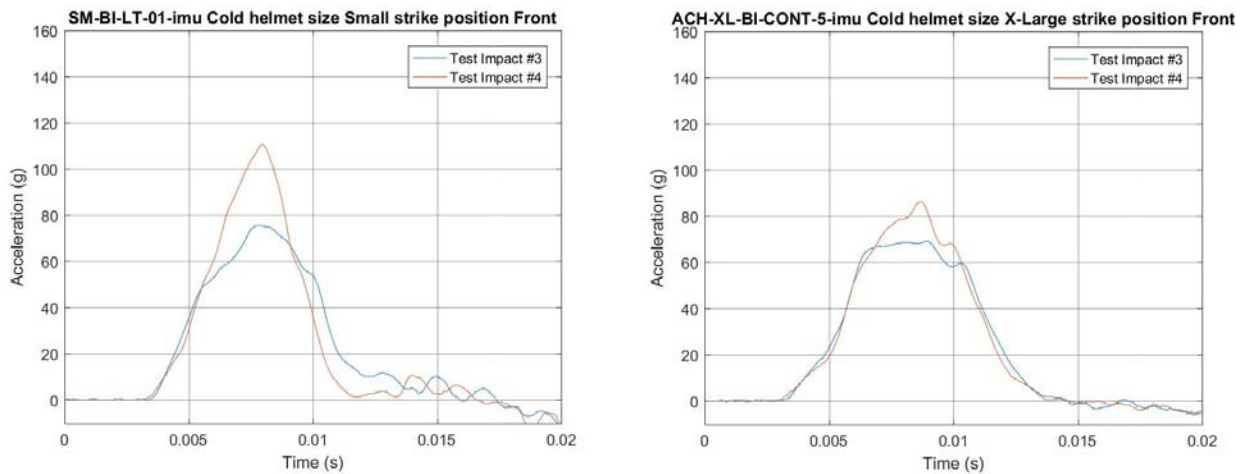


Figure 5. Acceleration data traces of the front impact of a cold-conditioned helmet for sizes small (left) and extra-large helmet (right)

As with the other data break outs, a general trend can be observed that CTS averages the lowest, ATC the highest and NSRDEC somewhere in-between. ATC continues to show the lowest standard deviation on average.

Table 3. Break out by size - by Test Laboratory

N=84	Small			Medium			Large			X-Large		
Test laboratory	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC
Peak Acceleration (g)	81.7	77.8	78.5	80.2	74.1	74.6	77.8	73.2	75.3	75	69.1	73.7
Standard Deviation	16.2	18.9	17.2	16.8	20.7	20.9	13.2	15.0	13.5	14.3	13.2	15.7



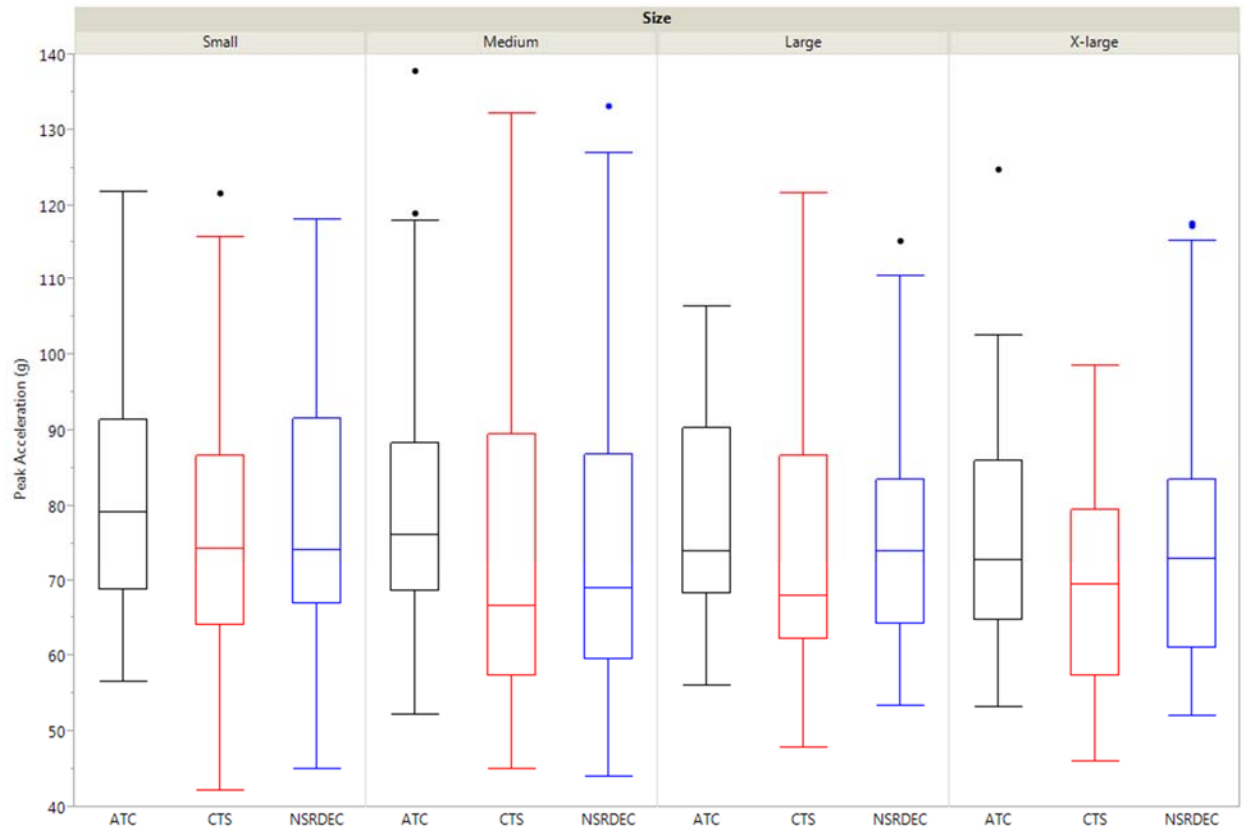


Figure 6. Break out by size - by Test Laboratory

### Comparison by condition

The test method calls out three environmental conditions to be evaluated. The two extremes, hot (54.4 +/- 3 °C) and cold (-10 +/- 3 °C), and ambient (21 +/- 10 °C). Two of the helmets for each size are conditioned at each of these specified temperatures for at least 12 h prior to testing.

This section breaks out the data by environmental conditioning. The cold helmets experienced the highest impact accelerations due to the increased stiffness of the helmet pads. The hot condition data sets have the most variation with higher standard deviations for NSRDEC and ATC. Often the helmets conditioned at elevated temperature require more adjustments to affix to the head-form, due to the reduced pad stiffness. A less experienced test laboratory may have more variation in helmet set up time. Any helmets evaluated earlier in the 5 min time span (maximum out of chamber time permitted by the test method) will likely react differently than those impacted later, which would have had more time to cool off.

As with previous data sets, it can be found that the peak acceleration data from CTS averages the lowest, ATC the highest and NSRDEC somewhere in between. While ATC generally has the lowest standard deviation, CTS the highest and NSRDEC somewhere in between.

Table 4. Break out by condition - by Test Laboratory

N=112	AMBIENT			COLD			HOT		
Test Laboratory	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC
Peak Acceleration (g)	75.0	70.0	73.0	86.2	81.1	78.9	74.8	69.5	74.7
Standard Deviation	14.2	16.7	15.9	13.8	16.7	15.7	15.2	16.6	19.0

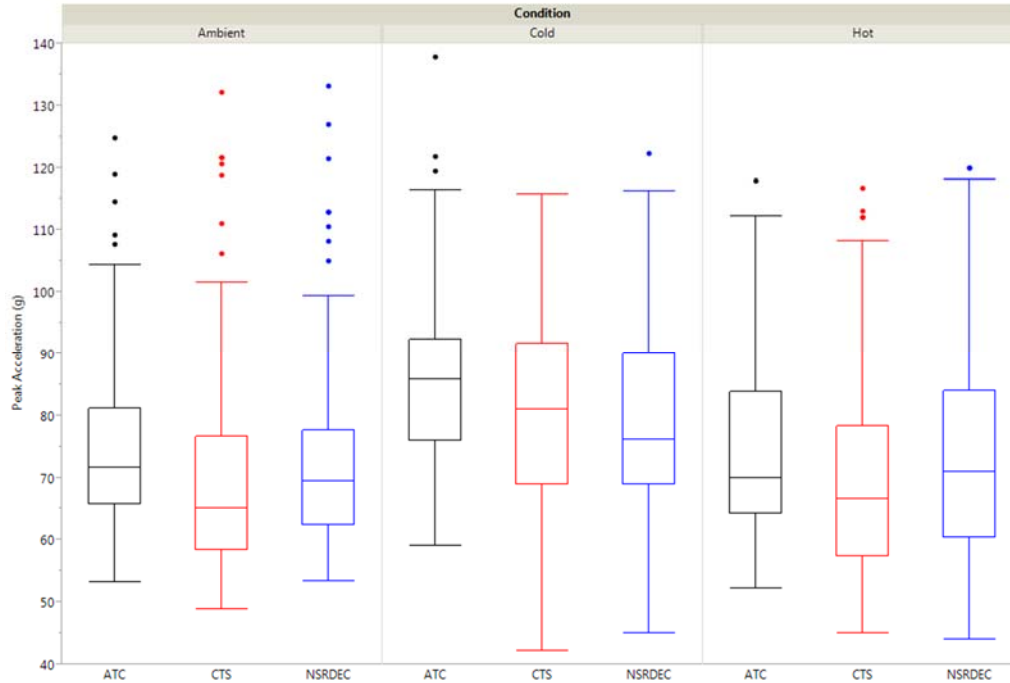


Figure 7. Break out by condition - by Test Laboratory

### Comparison by impact

In this data set, the first impact at every test location is compared to the second impact at every test location. The second impact is taken between 60 and 120 s after the first impact, which does not permit the liner system to fully “relax” or recover, as can be seen in the data below. This compression of the pads has two main effects on the second impact. The first being that the lower volume of the pads alters the closeness of fit between the helmet liner system and the head-form, which can increase experimental variance. The second effect is a reduction in pad thickness by densification. In this process, the helmet pads become mechanically stiffer and lose some potential stroke, resulting in a slightly less efficient energy absorber. Another source of discrepancy between first and second impacts (for the hot and cold conditioned helmets) is that helmet temperature will change over the time interval between tests.

As expected when the data are broken out by impact, the second impact displays a slightly higher variation and a slightly higher peak acceleration. The larger standard deviation is thought to be at least connected to the variation in the time between the first impact and the second impact, allowing the pad

to relax or recover to differing extents. Also of note is the observation that, despite the tighter standard deviations, both ATC and NSRDEC showed many more outliers for the initial impact tests when compared to the secondary impact tests. All of the same trends apply with ATC exhibiting the highest peak acceleration and lowest standard deviation, CTS exhibiting the lowest peak acceleration and NSRDEC in between.

Table 5. Break out by impact – by Test Laboratory

N=168	Impact 1			Impact 2		
Test Laboratory	ATC	CTS	NSRDEC	ATC	CTS	NSRDEC
Peak Acceleration (g)	74.9	69.1	71.3	82.4	77.9	79.8
Standard Deviation	14.2	15.7	15.4	15.7	18.0	17.7

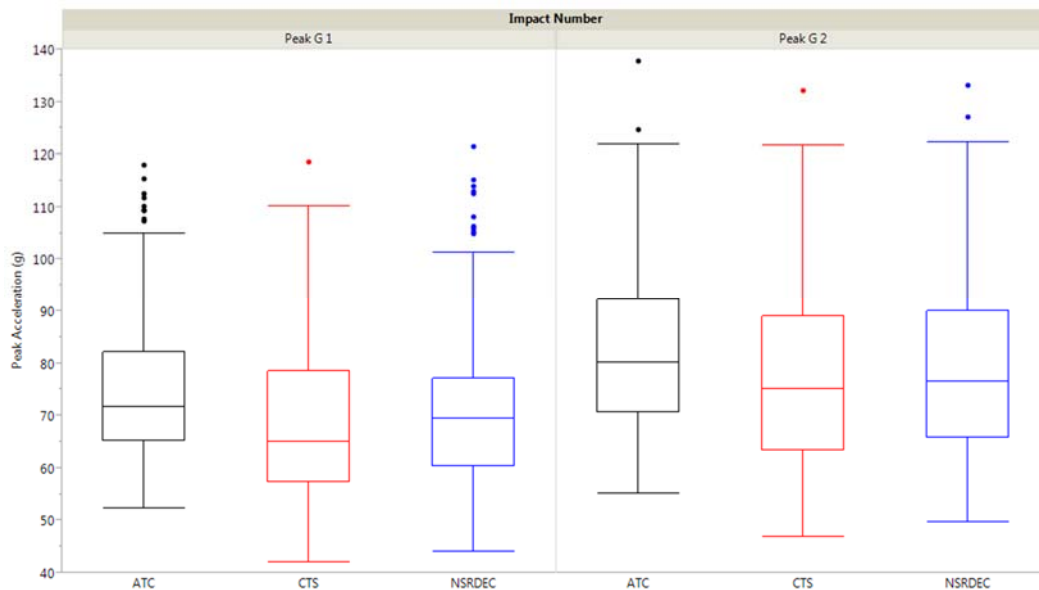


Figure 8. Break out by impact – by Test Laboratory

## Discussion

Levene's Test was performed on the entire data set, in aggregate, to assess homogeneity of variance between each test laboratory. This was done in order to ensure that the variance in data from each test laboratory is equal, a necessary requirement to test for statistically significant differences with Analysis of Variance (ANOVA) tests. A confidence level of 95% giving an alpha level of 2.5% for each tail (alpha of 5% total for a two-tailed test) was used. The alpha level of 0.05 was assumed for all statistical calculations completed in this report. The result of the homogeneity test ( $p = 0.0574$ ) failed to reject the null hypothesis, meaning there were no statistically significant differences between the Test Laboratories' variance when aggregating the data.

In addition to comparing the variances of the three test labs, peak acceleration densities were drawn for data from all three labs in Figure 9 to assess the shape of their distributions. It appears that some part of the test method skews the data density toward lower peak acceleration instead of focusing around a central peak acceleration. This may be due to the differences in impact location peak accelerations having fewer locations with higher peak accelerations than lower. All three data sets were tested for normality and resulted in a 95% goodness of fit to a normal distribution. This is another important characteristic that is assumed during the ANOVA test, although deviations from a normal distribution may not be crucial to the validity of the test [5] [6].

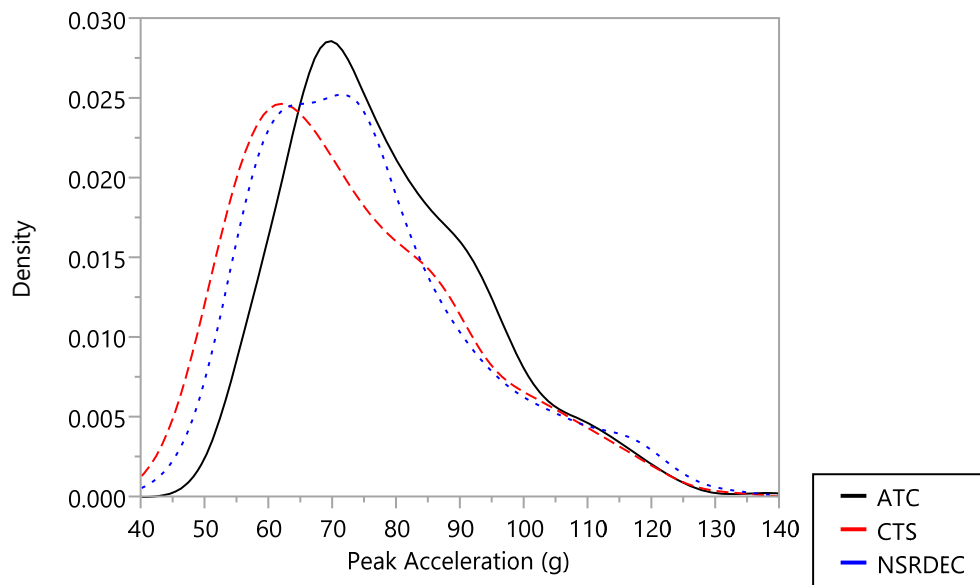


Figure 9. Density of peak acceleration data by Test Laboratory

Bayesian variance component estimation, using peak acceleration as the driving data metric, shows that the primary sources of variance are impact location and variability internal to the evaluated components labelled as "Within" (Table 6). It stands to reason that the impact location would cause high variation across the data set due to the fact that acceleration magnitudes are largely different at the multiple locations around the helmet. The component variable, Test Laboratory, was determined to be a small contributor to the variance (1.9%).

Table 6 Bayesian variance component estimates (main effects)

### Variance Components

Component	Var Component	% of Total	Plot%	Sqrt(Var Comp)
Size	7.11335	2.2		2.667
Condition	28.02791	8.5		5.294
Test Laboratory	6.36137	1.9		2.522
Impact Location	120.67734	36.5		10.985
Impact Number	33.92139	10.3		5.824
Within	134.66191	40.7		11.604
Total	330.76328	100.0		18.187

To statistically compare the test facilities results, an Analysis of Means (ANOM) and a Four-way ANOVA were computed. A confidence interval of 95% was used for all statistical tests in this report. The ANOM plot in Figure 10 displays the disparity between the test data for each of the laboratories when compared to the “Grand Mean,” or combined average of all data points from all data sets. When compared to the mean and variance of all available data, ATC data is significantly higher, CTS data is significantly lower, and NSRDEC data is close to the middle of the overall distribution and is not significantly different from the Grand Mean.

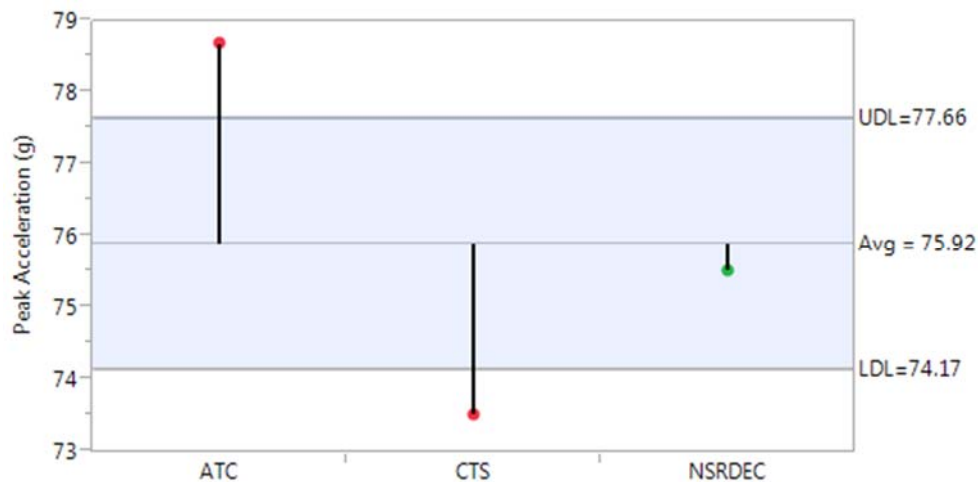


Figure 10. ANOM by Test Laboratory

In order to draw conclusions about the relationships between Test Laboratories, results from the ANOVA test were considered. As with all statistical tests in this report, a confidence interval of 95% was selected. This means that a 5% risk of committing a Type 1 error (incorrectly rejecting the null hypothesis when it is actually true) is accepted. The results of the four-way ANOVA test with effects and two-way interactions are reported in Table 7.

Table 7 N-way ANOVA

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Size	3	3	5781.68	31.4406	<.0001*
Condition	2	2	19104.08	155.8312	<.0001*
Test Laboratory	2	2	4544.16	37.0665	<.0001*
Impact Location	6	6	105073.20	285.6925	<.0001*
Impact Number	1	1	17231.04	281.1057	<.0001*
Size*Condition	6	6	7442.32	20.2356	<.0001*
Size*Test Laboratory	6	6	655.88	1.7833	0.0994
Size*Impact Location	18	18	33419.80	30.2893	<.0001*
Size*Impact Number	3	3	247.91	1.3481	0.2574
Condition*Test Laboratory	4	4	2110.67	8.6083	<.0001*
Condition*Impact Location	12	12	27923.82	37.9622	<.0001*
Condition*Impact Number	2	2	336.07	2.7413	0.0650
Test Laboratory *Impact Location	12	12	2116.41	2.8772	0.0007*
Test Laboratory *Impact Number	2	2	73.43	0.5989	0.5496
Impact Location*Impact Number	6	6	2876.82	7.8220	<.0001*
Error		922	56516.17		
C. Total		1007	285453.44		

The ANOVA test results conclude no significant difference between Test Laboratories; the null hypothesis is true. However, this result alone does not indicate a significant relationships between specific laboratories. Therefore, it was necessary to perform a Tukey-Kramer Honest Significant Difference (HSD) post-hoc analysis of the data, as seen in Table 8. A graphical representation (diffogram) of the Tukey-Kramer test is illustrated in Figure 11. The graph displays the confidence intervals for all mean pairwise differences between the three Test Laboratories. The color of the line indicates whether the differences are significant, in this case all the lines are red, indicating a significant difference between each Test Laboratory. Similarly to the ANOM test, CTS data falls on the low end, ATC data is at higher values, and NSRDEC data lies in between.

Table 8 Tukey-Kramer HSD, all pairwise differences

Test Facility	-Test Facility	Difference	Std Error	t Ratio	Prob> t	Lower 95%	Upper 95%
ATC	CTS	5.15774	0.6040408	8.54	<.0001*	3.73975	6.57572
ATC	NSRDEC	3.15744	0.6040408	5.23	<.0001*	1.73946	4.57543
CTS	NSRDEC	-2.00030	0.6040408	-3.31	0.0028*	-3.41828	-0.58231

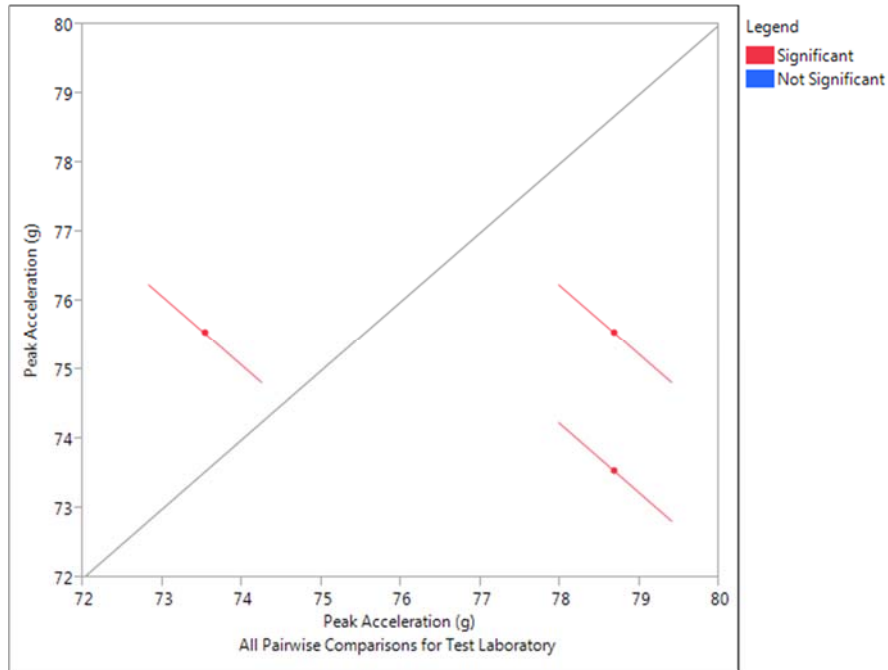


Figure 11. Tukey-Kramer HSD

Although the laboratories are statistically significantly different from each other, this does not mean that the data from any of the three laboratories are necessarily invalid, only that there is some difference between the results at each test laboratory. An Equivalence TOST (Two One-Sided Tests) was performed to evaluate the practical difference between the labs. Using a threshold mean acceleration difference of 7g or greater shows no practical difference between the three Test Laboratories. This denoted by the resulting p-values being far less than the alpha value ( $\alpha=0.05$ ) for all three comparisons in Table 9.

Table 9 Equivalence TOST test, mean difference of 7g

Test Facility	-Test Facility	Difference	Lower Bound t Ratio	Upper Bound t Ratio	Lower Bound p-Value	Upper Bound p-Value	Max p-Value
ATC	CTS	5.15774	-3.0499	20.12735	0.0033*	<.0001*	0.0033*
ATC	NSRDEC	3.15744	-6.3614	16.81582	<.0001*	<.0001*	<.0001*
CTS	NSRDEC	-2.00030	-14.9001	8.27709	<.0001*	<.0001*	<.0001*

## Conclusions

Three Test Laboratories performed the Army's standardized blunt impact test procedure. Each laboratory used similar test equipment and followed the same test procedure developed by ATC. The test samples were all of the same type, although not from the same lot or manufacturer, and as such small differences may exist between the test samples. All three laboratories came to the same result in that the tested equipment passed the blunt impact test. It is recommended that an acceptability criteria is established in the future to provide an acceptable range of results between laboratories. A recommendation for that criteria is described in Appendix D – Acceptability Criteria.

Overall the same conclusions and trends were seen at each test laboratory. Smaller helmets had higher peak accelerations than larger helmets. Cold helmets had higher peak accelerations than other conditions. The second impact had a higher peak acceleration than the first. The front and nape locations had higher peak accelerations than the other locations.

The results of this effort support the conclusion that the Test Laboratories are consistently impacting the specimens at the same velocities well within tolerances. The recorded acceleration data showed statistically significant differences between Test Laboratories. However, the equivalence test shows, within a designated range, the Test Laboratories can be determined practically equivalent.

The primary conclusion is that NSRDEC is capable of conducting blunt impact tests and obtaining results within the ranges observed by Army accredited laboratories, making NSRDEC a viable test resource for blunt impact.

This document reports research undertaken at the U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, and has been assigned No. NATICK/TR- 18/006 in a series of reports approved for publication.



## References

- [1] M. Bruggeman, "INTERNAL OPERATING PROCEDURE No. 029 REV E - BLUNT IMPACT TESTING PROCEDURE FOR COMBAT HELMETS," ABERDEEN TEST CENTER WARFIGHTER DIRECTORATE MATERIALS & MEASUREMENTS TEST BRANCH.
- [2] P. S. E. TMD, "'Purchase Description, Helmet, Advanced Combat (ACH)" CO/PD-05-04 pp. 32," Program Executive Office – Soldier, Fort Belvoir, VA, 2007.
- [3] B. J. McEntire, "Blunt Impact Performance Characteristics of the ACH and the Paratrooper and Infantry PASGT," DTIC, Fort Belvoir VA, August 2005.
- [4] SAE, *Instrumentation for Impact Test - Part 1 - Electronic Instrumentation J211-1*, SAE International, Issued 1971 Revised 2014.
- [5] P. D. P. J. R. S. Gene V Glass, "Consequences of Failure to Meet Assumptions Underlying the Fixed Effects Analyses of Variance and Covariance," *Sage Journals*, vol. 42, no. 3, 1972.
- [6] M. Harwell, "Summarizing Monte Carlo Results in Methodological Research: The Single-Factor, Fixed-Effects ANCOVA Case," *Journal of Educational and Behavioral Statistics*, vol. 28, no. 1, pp. 45-70, 2003.
- [7] D. o. t. Army, "Technical Manual Operator's Manual for Advanced Combat," 2004.
- [8] U. D. o. Transportation, "'Laboratory Test Procedure for Motorcycle Helmets." FMVSS No. 218. TP-218-06," National Highway Traffic Safety Administration - Office of Vehicle Safety Compliance, Washington DC, 30 November 2006.
- [9] D. o. t. Army, "Helmet, Flyer's, Protective, SPH-4. MIL-H-43925A," 1980.
- [10] B. Slobodnik, "SPH-4 helmet damage and head injury correlation USAARL-80-7," Fort Rucker, AL, 1980.
- [11] B. J. McEntire, "Blunt Impact Performance of the US Marine Corps Light Weight Helmet (LWH) and the US Army Advanced Combat Helmet (ACH) with Fielded and Alternative Fitting Systems," WARFIGHTER PROTECTION DIVISION, 2006.
- [12] J. Hopping, "Methodologies for Blunt Trauma Assessment in Military Helmets".

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## Appendix A – Advanced Combat Helmets, Furnished

### ATC

Size	Vendor	Lot# or W/O#	Serial number	ID number
Small	Revision	L# 5190	S-V081606	ATC-S-1
			S-V081674	ATC-S-2
			S-V081672	ATC-S-3
			S-V081680	ATC-S-4
			S-V081677	ATC-S-5
			S-V081673	ATC-S-6
			S-V081679	ATC-S-7
			S-V081675	ATC-S-8
Medium	SDS	w/o# 53-7138	010120878	ATC-M-1
			010120871	ATC-M-2
			010120873	ATC-M-3
	BAE	w/o# 54-1580	010253674	ATC-M-4
			010253669	ATC-M-5
	SDS	w/o# 53-5418	010035575	ATC-M-6
		w/o# 53-6967	010112607	ATC-M-7
		w/o# 53-5024	010023939	ATC-M-8
Large	SDS	w/o# 53-7600	010133444	ATC-L-1
			010133408	ATC-L-2
			010133445	ATC-L-3
			010133452	ATC-L-4
			010133446	ATC-L-5
	MSA	L#2019	L-M260432	ATC-L-6
			L-M260435	ATC-L-7
			L-M260436	ATC-L-8
X-Large	MSA	HD-D-008	<del>X-V315882</del>	<del>ATC-XL-1</del>
			<del>X-V315925</del>	<del>ATC-XL-2</del>
			<del>X-V315899</del>	<del>ATC-XL-3</del>
			<del>X-V315917</del>	<del>ATC-XL-4</del>
			<del>X-V315883</del>	<del>ATC-XL-5</del>
			<del>X-V315929</del>	<del>ATC-XL-6</del>
			X-V315910	ATC-XL-7
	Gentex	L# 252	0301453	ATC-XL-8

\*Note first six X-Large helmets were tested on the DOT C head-form in error, ATC provided four more helmets which were used in conjunction with the two contingency helmets, and those serial numbers were not recorded

## Chesapeake

Size	Vendor	Lot# or W/O#	Serial number	ID number
Small	Revision	L# 5190	S-V081657	CT-S-1
			S-V081653	CT-S-2
			S-V081655	CT-S-3
			S-V081658	CT-S-4
			S-V081656	CT-S-5
			S-V081659	CT-S-6
			S-V081661	CT-S-7
			S-V081660	CT-S-8
Medium	SDS	w/o# 53-7138	010120872	CT-M-1
			010120877	CT-M-2
			010120875	CT-M-3
	BAE	w/o# 54-1580	010253667	CT-M-4
			010253671	CT-M-5
	SDS	w/o# 53-5418	010035578	CT-M-6
	BAE	w/o# 54-1983	010277281	CT-M-7
	SDS	w/o# 53-6689	010098085	CT-M-8
Large	SDS	w/o# 53-7600	010133387	CT-L-1
			010133386	CT-L-2
			010133391	CT-L-3
			010133389	CT-L-4
			010133388	CT-L-5
	MSA	L#2019	L-M260441	CT-L-6
			L-M260433	CT-L-7
			L-M260434	CT-L-8
X-Large	MSA	HD-D-008	X-V315904	CT-XL-1
			X-V315877	CT-XL-2
			X-V315902	CT-XL-3
			X-V315891	CT-XL-4
			X-V315935	CT-XL-5
			X-V315920	CT-XL-6
			X-V303779	CT-XL-7
	Gentex	L# 252	0301450	CT-XL-8

## NSRDEC

Size	Vendor	Lot# or W/O#	Serial number	ID number
Small	Revision	L# 5190	S-V081678	N-S-1
			S-V081676	N-S-2
			S-V081654	N-S-3
			S-V081652	N-S-4
			S-V081603	N-S-5
			S-V081681	N-S-6
			S-V081605	N-S-7
			S-V081604	N-S-8
Medium	SDS	w/o# 53-7138	010120874	N-M-1
			010120870	N-M-2
			010120875	N-M-3
	BAE	w/o# 54-1580	010253665	N-M-4
			010253673	N-M-5
	SDS	w/o# 53-5418	010035582	N-M-6
	BAE	w/o# 54-1580	010253672	N-M-7
	SDS	w/o# 53-7774	010136982	N-M-8
Large	SDS	w/o# 53-7600	010133384	N-L-1
			010133385	N-L-2
			010133383	N-L-3
			010133390	N-L-4
			010133392	N-L-5
	MSA	L#2019	L-M260438	N-L-6
			L-M260437	N-L-7
			L-M260440	N-L-8
X-Large	MSA	HD-D-008	X-V315880	N-XL-1
			X-V315941	N-XL-2
			X-V315912	N-XL-3
			X-V315913	N-XL-4
			X-V315893	N-XL-5
			X-V315888	N-XL-6
			X-V315919	N-XL-7
	Gentex	L# 252	0301452	N-XL-8

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## Appendix B – Test Lab Information

Although every laboratory followed ATC's IOP for blunt impact testing, which is far more restrictive than the previous requirements, each laboratory had their own procedural differences due to laboratory set up and interpretation of the procedure.

### NSRDEC

#### Operators

The NSRDEC test was run by two of NSRDEC's personnel; one in charge of collecting helmets and running data acquisition, and the other in charge of positioning helmets and operating the control panel. The operators were the same throughout the entire test.

#### Laboratory Set up

NSRDEC's blunt impact laboratory is very small compared to the other Test Laboratories. A safety cage resided around the Cadex Uniaxial Monorail. The low temperature environmental chamber resides immediately to the right of the Cadex uniaxial monorail and the high temperature chamber resides in a separate room. The computer controlling Cadex's software resides across from the monorail making visual height readings difficult.

#### HPI

To measure the Helmet Position Index (HPI) a steel bar with a line denoting the HPI length was used as a guide. It was used to measure in two places to help ensure the helmet was positioned evenly. HPI is known as the distance from the rim of the helmet to the first line on the DOT head-form. This distance is different for each helmet size and is called out in ATC's IOP.

#### Chin Forms

Foam chins were supplied from ATC. They were hand cut using a pocket knife by personnel at ATC. These chin shapes are considered the official standard.

#### Head-form Alignment Tool (HAT)

Experience in changing the head-form impact location proved that when tightening the four bolts which lock the head-form into position it causes slight variations to the head-form's position. Using the Mitutoyo digital protractor proved only capable of aligning the head-form to at most two of the three axes of rotation. A tool was developed to align the head-form for each impact location in all three rotational axes. This tool was used to align the head-form each time the impact location changed.

#### Equipment

- Espec environmental chamber
- Binder Oven
- Cadex uniaxial monorail tower
- Mitutoyo digital protractor
- Head-form Alignment Tool (HAT)



*Figure C-1 NSRDEC Impact Laboratory*



## ATC

### Operators

Multiple operators were used at ATC. It was noted that one to three operators were participating in the test. This fluctuated as interns were pulled to and from other tasks. One operator stayed consistent throughout the test, manipulating the helmet and head-forms. The other operators timed how long samples were out of their respective environmental chambers and controlled the software.

### HPI

ATC used 3D printed HPI tools, which provided two contact points ensuring the helmet was positioned evenly.

### Helmet Alignment

A notable procedural difference from the other labs was that ATC moved the H-back above the head-form to keep the helmet from falling forward. This procedure was mimicked by NSRDEC and found a successful strategy as the DOT head-form's shape does not permit a good fit with the H-back in the intended location.

When testing XL, sometimes the release mechanism had to be manually released due to low air pressure.

A digital level was used for alignment.

A standard hex wrench was used for tightening.

### Equipment

- Head Position Index tool
- Cincinnati Sub-zero model Z32 plus
- Envirotronics
- Cadex uniaxial monorail tower
- Mitutoyo digital protractor



*Figure C-2 Aberdeen Test Center Blunt Impact Laboratory*

## CTS

### Operators

Only a single operator was used to perform the test.

### HPI

The operator used a caliper to set HPI from two location before each test.

### Helmet Alignment

During the later portions of the test procedure, specifically the nape impact locations, the operator tightened the front straps past halfway. This is technically a lapse in procedure but the operator was unable to maintain helmet position without doing so. The CTS operator did not know that ATC moved the H-back above the head-form in these situations and did not want to change their procedure mid-test.

Although likely insignificant, it was noted that CTS used their own foam chins approximating dimension from ATC provided chins.

According to the test procedure, a mark was supposed to be placed  $\frac{1}{2}$ " above the NVG hole and used as the impact location. However, the procedure also required the impact location to be located at the lowest point of the helmet (Apex of helmet to the apex of anvil). CTS chose to follow the lowest point of the helmet requirement and did not place a mark  $\frac{1}{2}$ " above the NVG hole. Both ATC and NSRDEC followed procedure for impacting at the indicated marking  $\frac{1}{2}$ " above the NVG hole.

A digital level was used for alignment.

A ratcheting hex wrench was used for tightening.

### Equipment

- Caliper
- SO-LOW Model C4G-9
- Thermolyne Model LC-8
- Cadex uniaxial monorail tower
- Mitutoyo digital protractor



*Figure C-3 Chesapeake Testing Blunt Impact Laboratory*

## Appendix C— Acceleration Corridors

In this appendix, acceleration corridors are plotted. Corridor plots show the entire acceleration curve providing more visual information than peak acceleration alone. Each plot compares the three labs broken out the same fashion as the report.

### Break out by laboratory

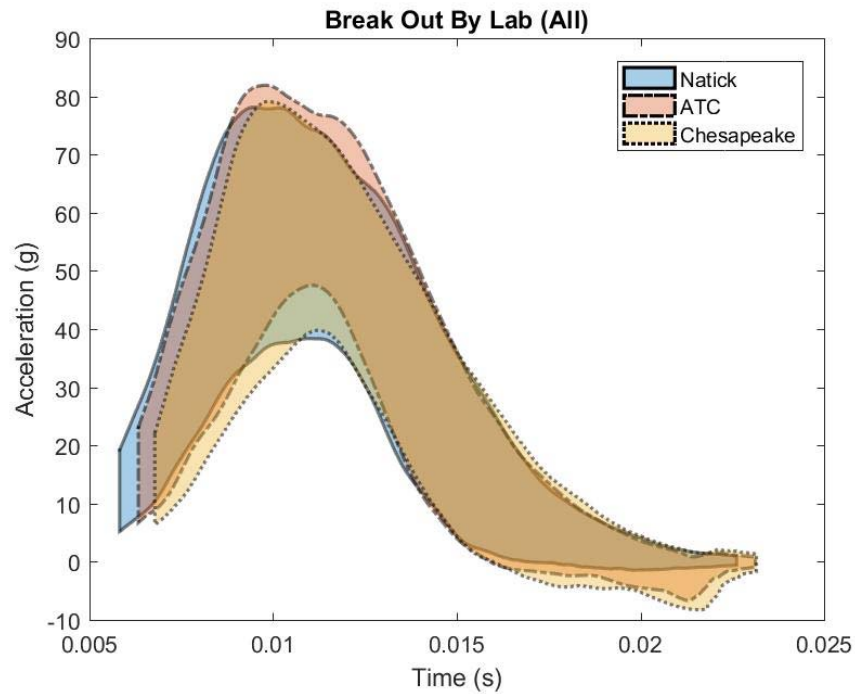


Figure C-1 Acceleration corridor, by Test Laboratory

## Breakout by impact location

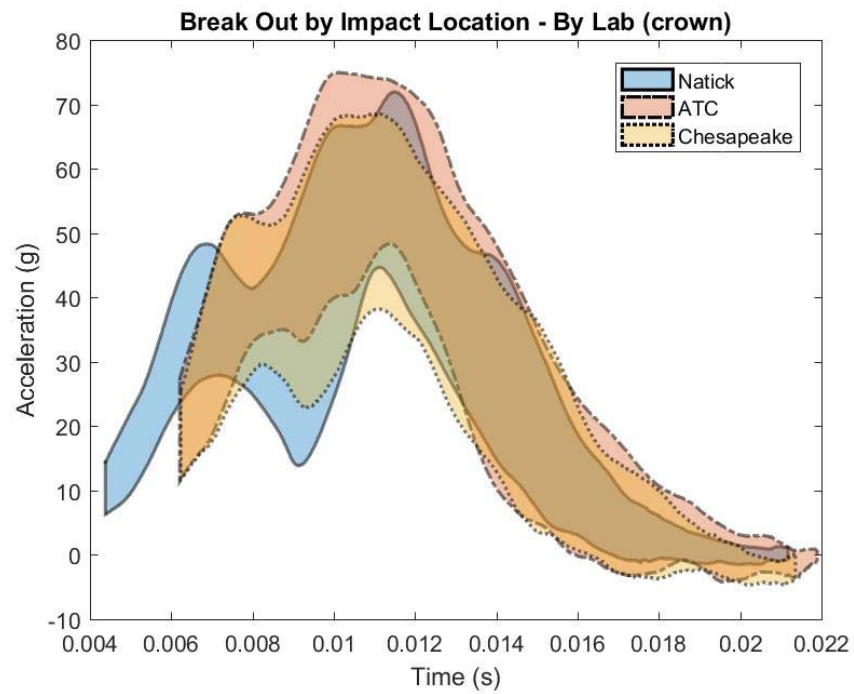


Figure C-2 Acceleration corridor, impact location = crown

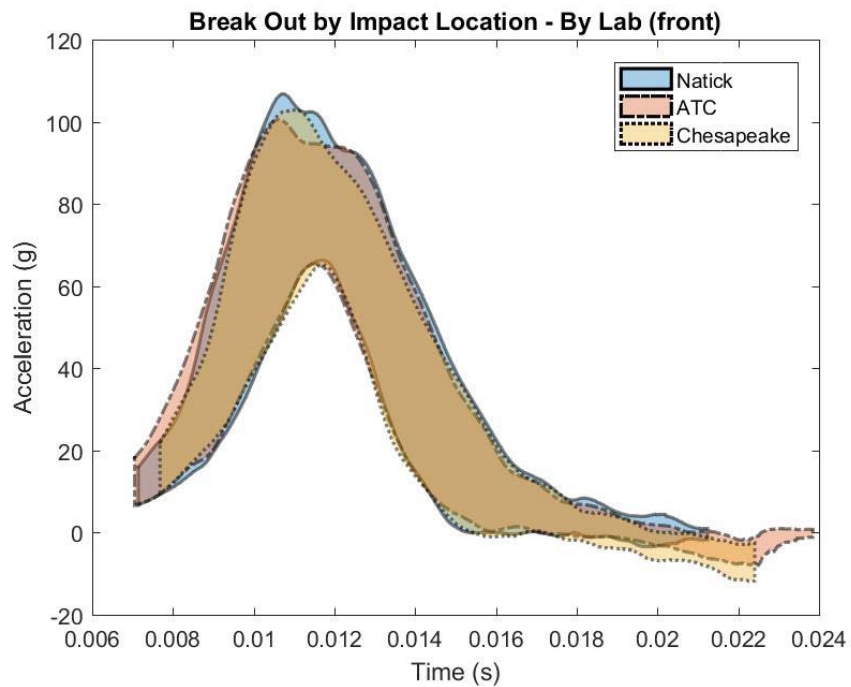


Figure C-3 Acceleration corridor, impact location = front

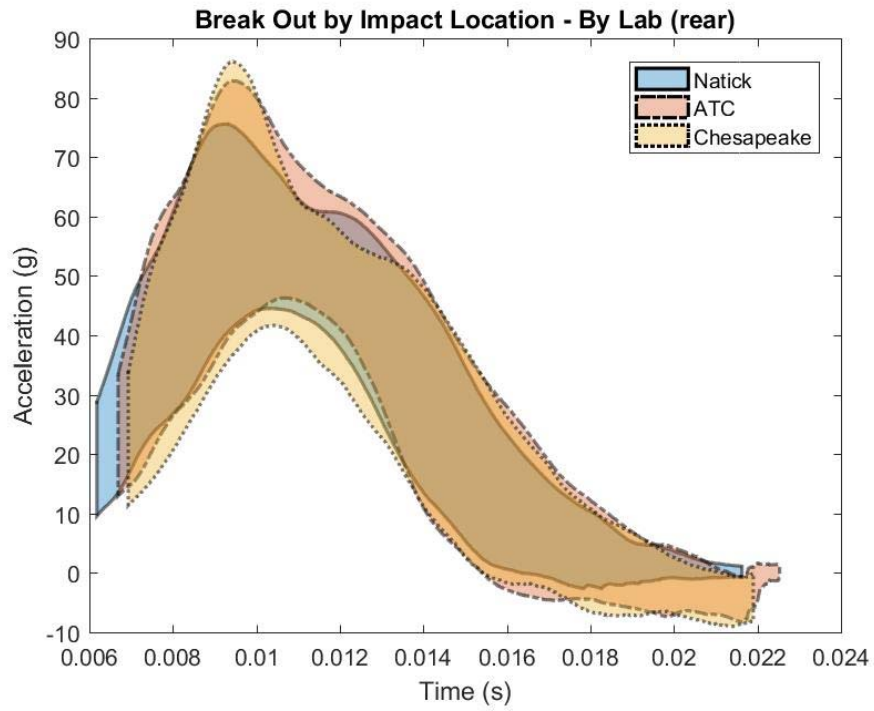


Figure C-4 Acceleration corridor, impact location = rear

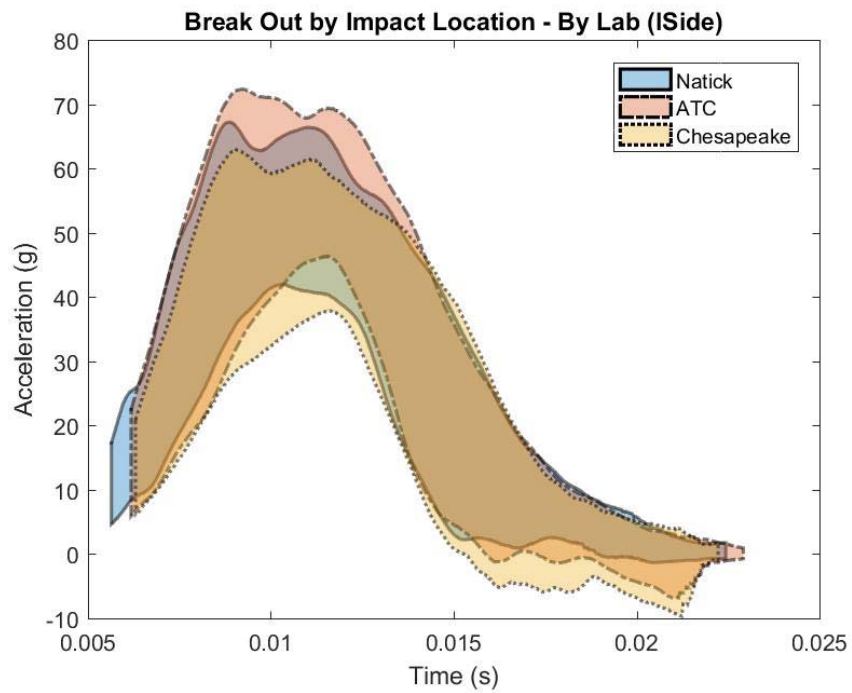


Figure C-5 Acceleration corridor, impact location = left side



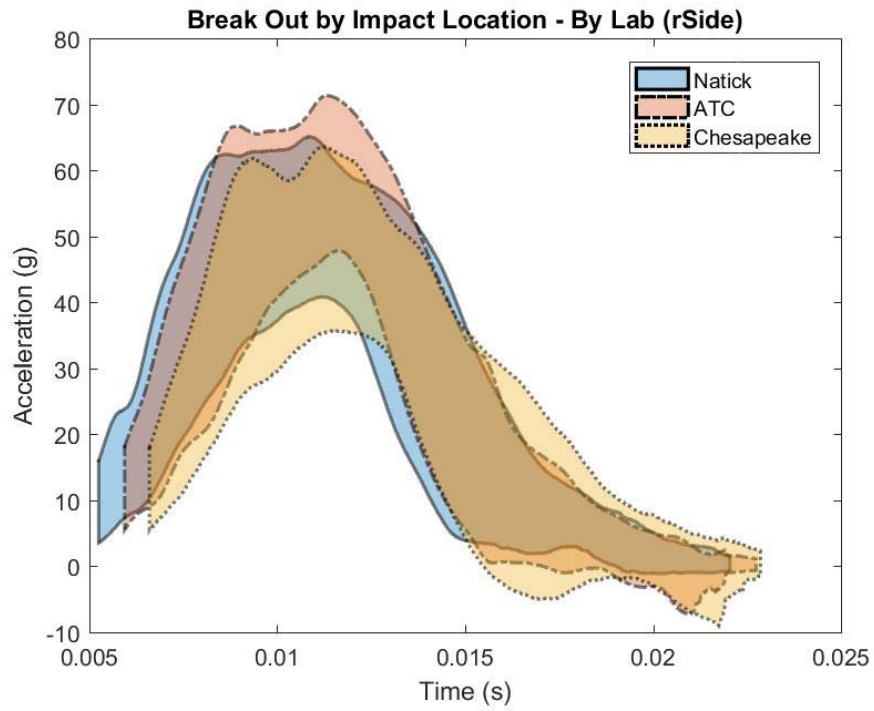


Figure C-6 Acceleration corridor, impact location = right side

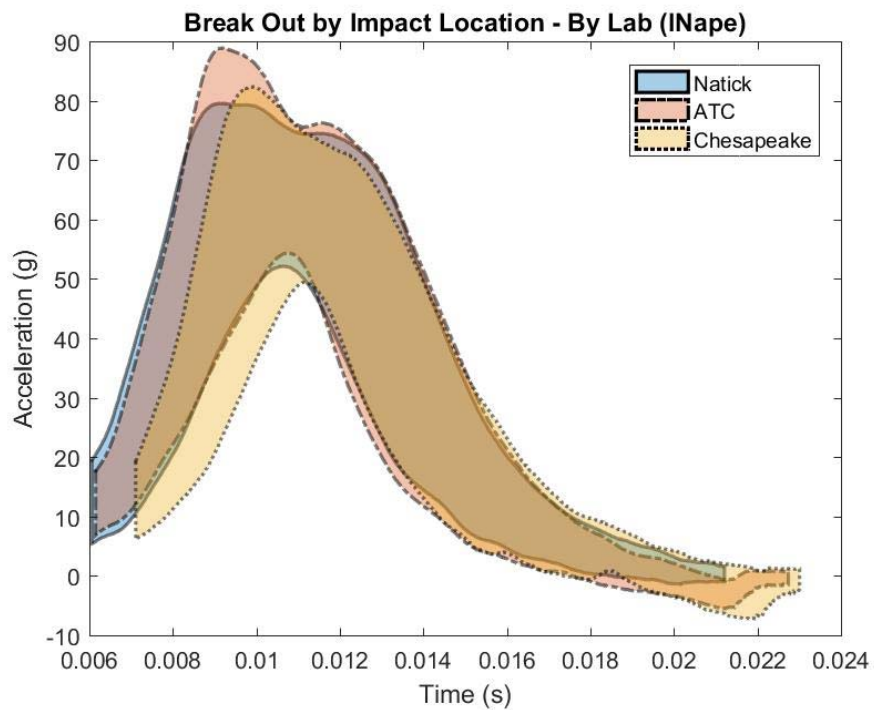


Figure C-7 Acceleration corridor, impact location = left nape



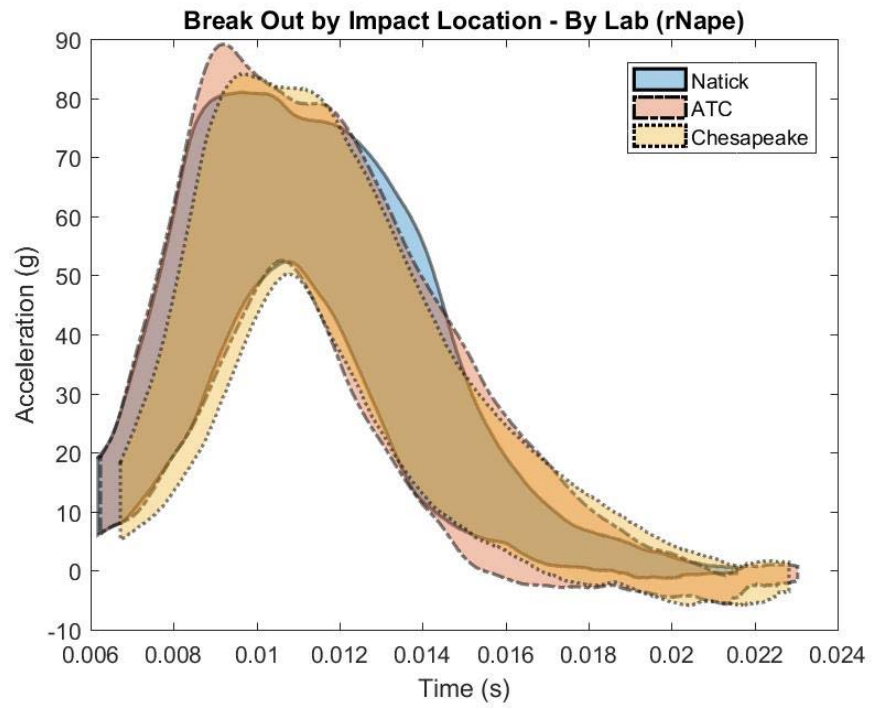


Figure C-8 Acceleration corridor, impact location = right nape

## Breakout by size

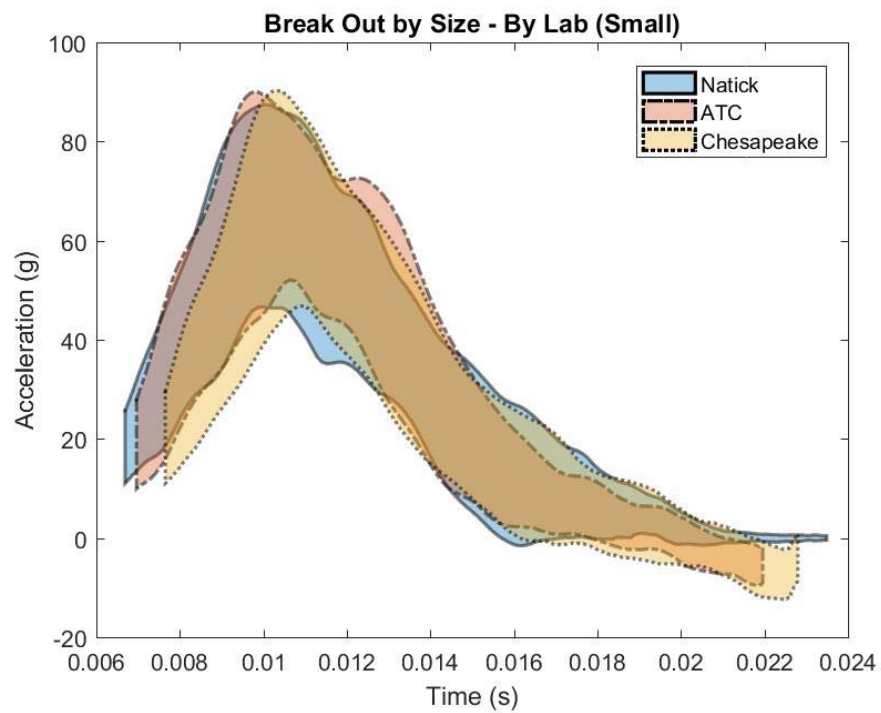


Figure C-9 Acceleration corridor, size = small

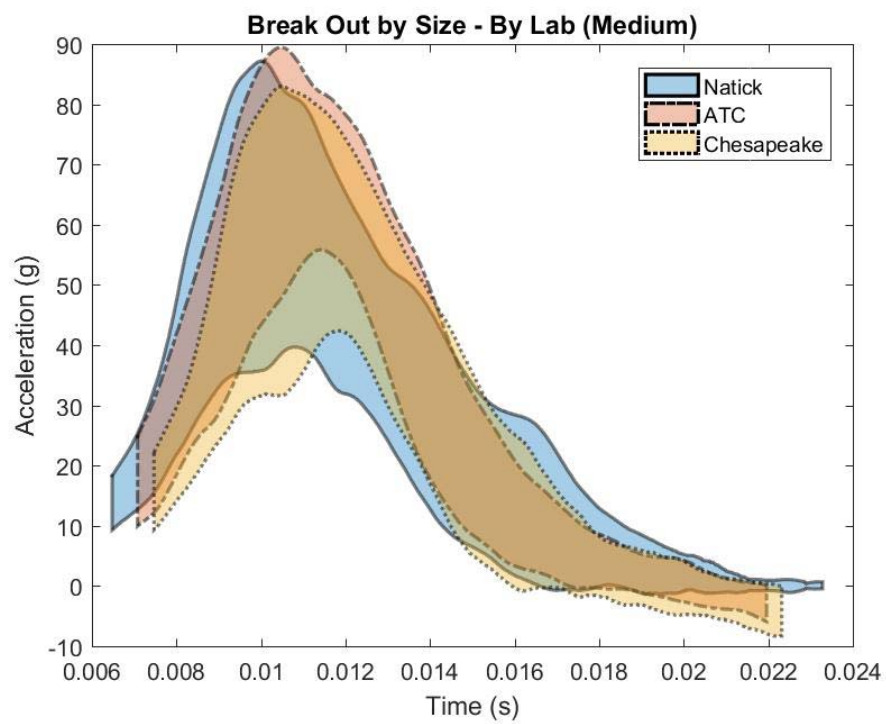


Figure C-10 Acceleration corridor, size = medium

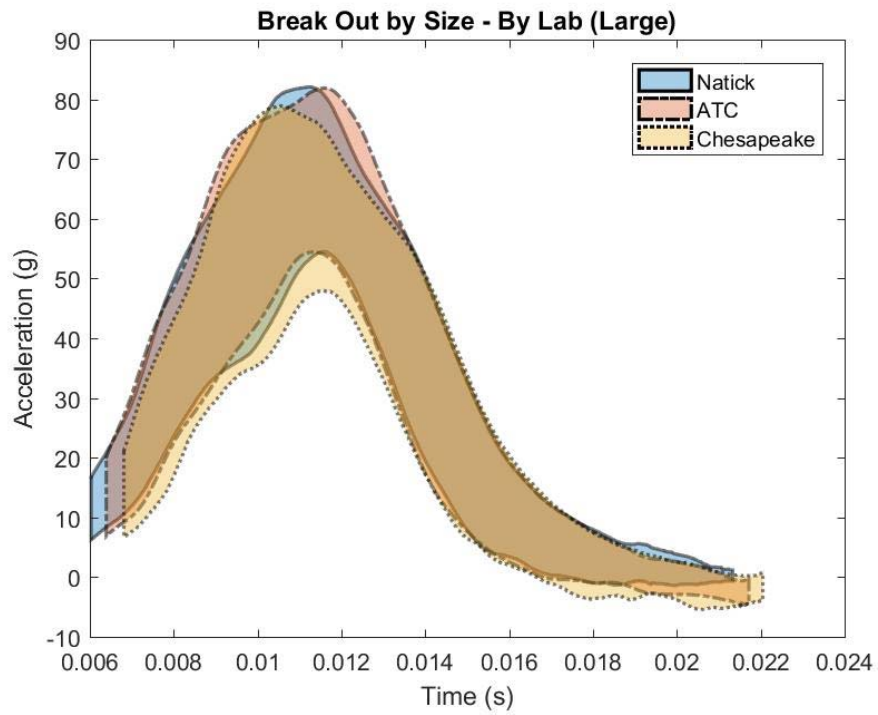


Figure C-11 Acceleration corridor, size = large

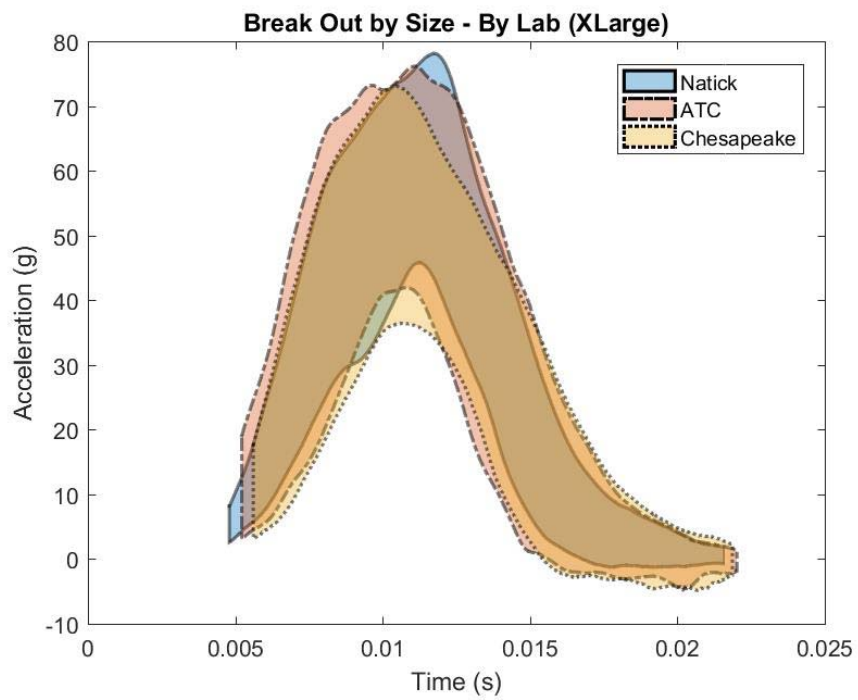


Figure C-12 Acceleration corridor, size = X-large

## Breakout by condition

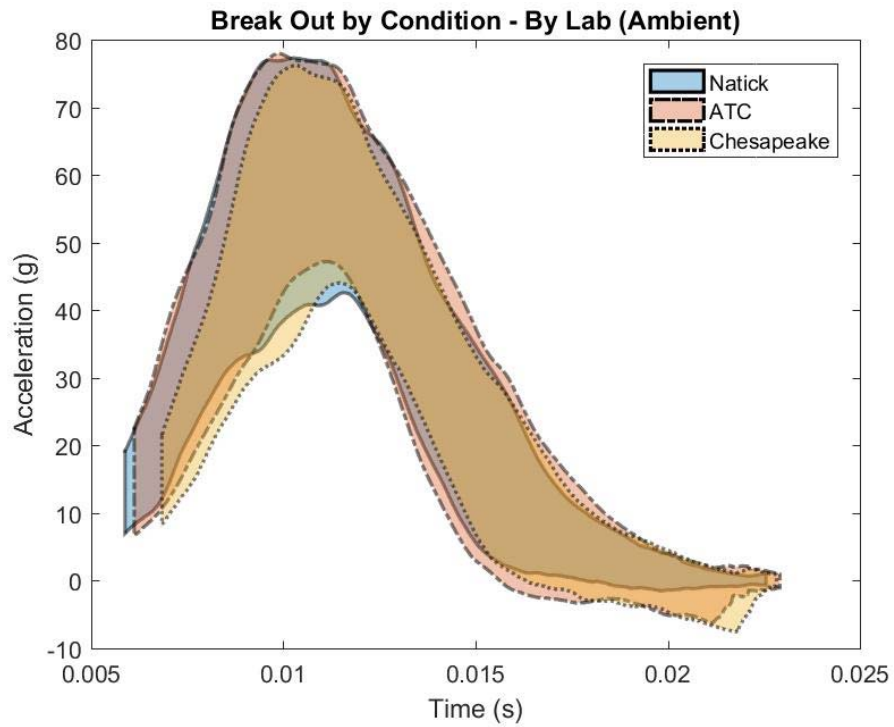


Figure C-13 Acceleration corridor, condition = ambient

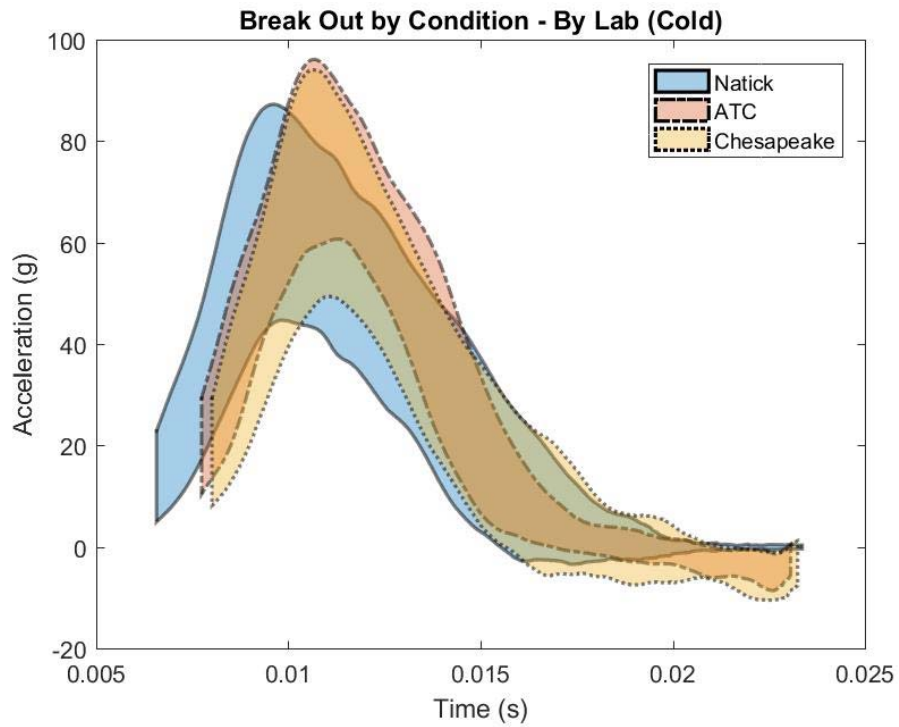


Figure C-14 Acceleration corridor, condition = cold

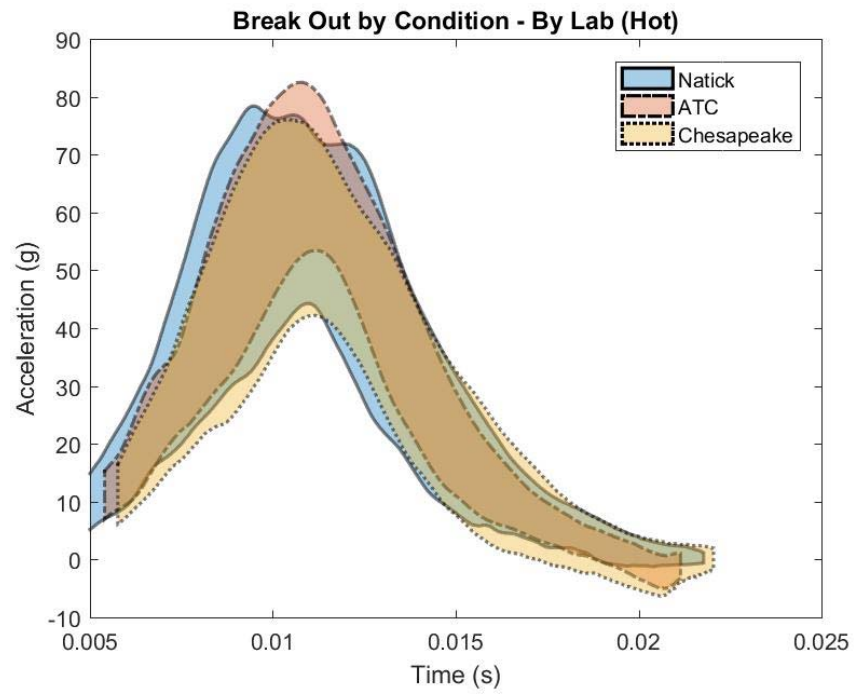


Figure C-15 Acceleration corridor, condition = hot

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## Appendix D - Acceptability Criteria

No standard has been developed in which the three Test Laboratories can be compared. The most variation was found in the variable impact location, making it difficult to aggregate that data for true comparison between laboratories. It is recommended that a range of accelerations for each impact location be developed for inter-laboratory comparison. A standardized test sample would need to be chosen (potentially the ACH) for comparison. A test laboratory whose data falls within the acceptable range would be considered validated. In Figure D-1 the aggregate data from the three Test Laboratories is plotted by impact location for the first and second impact. An upper bound could be chosen as one standard deviation above the average of Impact #2 and a lower bound could be chosen as one standard deviation below impact #1. A test laboratory could be considered valid if the average acceleration at each impact location is within those bounds.

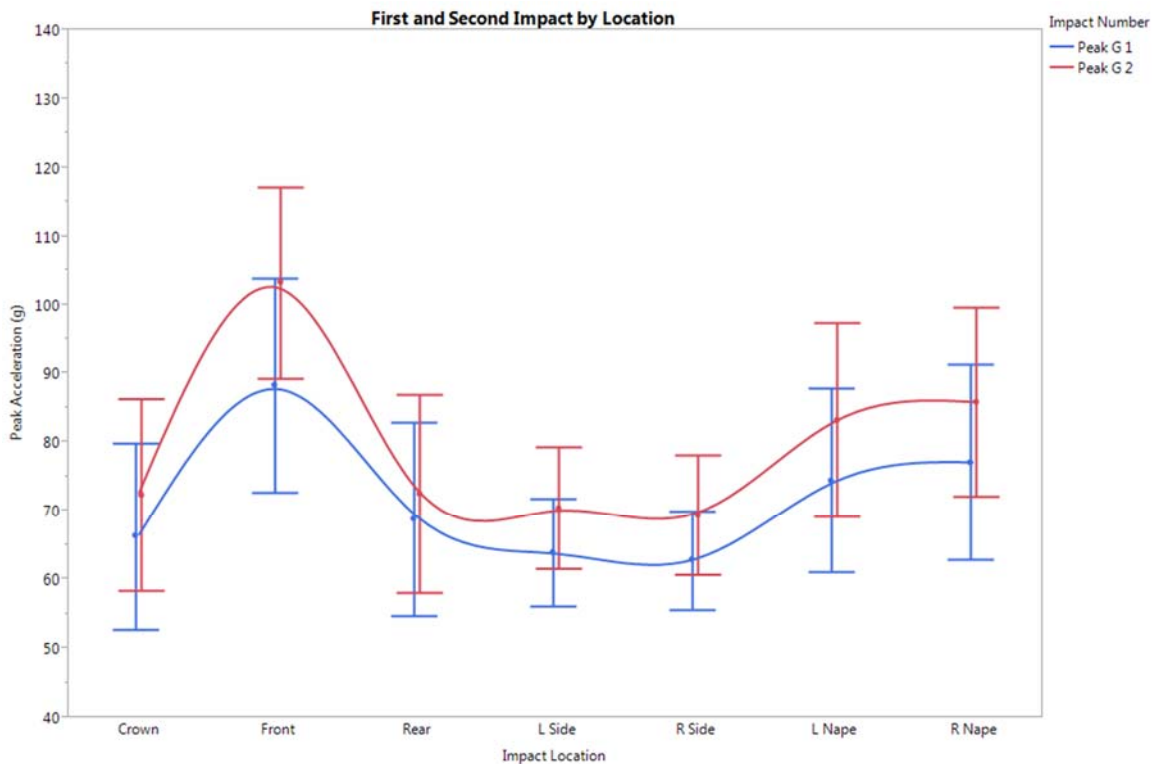


Figure D-1 First and second impact by location

Table D-1 Recommended acceptable range (for the ACH) - average peak acceleration (g)

Location	Crown	Front	Rear	L Side	R Side	L Nape	R Nape
Upper Bound	90	120	90	85	85	110	110
Lower Bound	50	70	50	50	50	60	60

*Table D-2 Resulting average peak acceleration (g) of each Test laboratory at each impact location*

Location	Crown	Front	Rear	L Side	R Side	L Nape	R Nape
ATC	72.78	96.26	72.82	71.16	70.19	83.30	84.31
CTS	67.60	95.08	71.41	62.49	61.99	76.31	79.85
NSRDEC	68.34	98.29	68.11	66.64	65.53	79.36	82.44